Must Advanced Fuel Cycles Produce High-Level Waste?

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If we had a great nuclear fuel cycle option today, we'd all be using it.

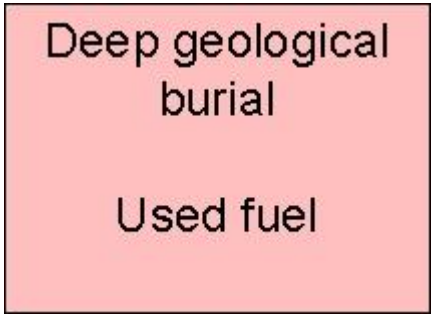
- Once-through has not been fully implemented in ***any*** country.
- Recycling has only been partially implemented, and not in the U.S.

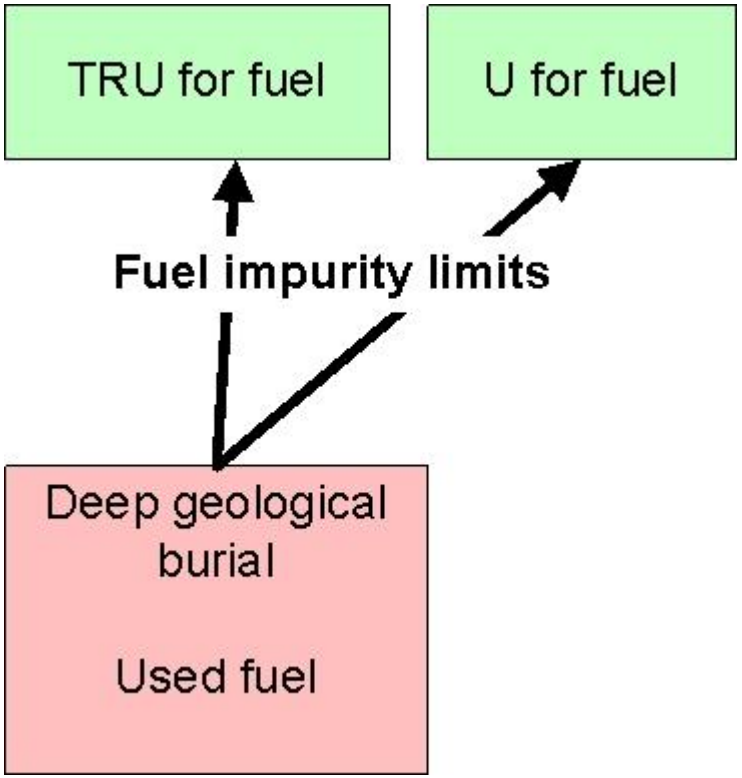
One definition of insanity is doing the same thing again and again (in the same circumstances) and expecting a different answer.

“Problems cannot be solved by the same level of thinking that created them.”

A. Einstein

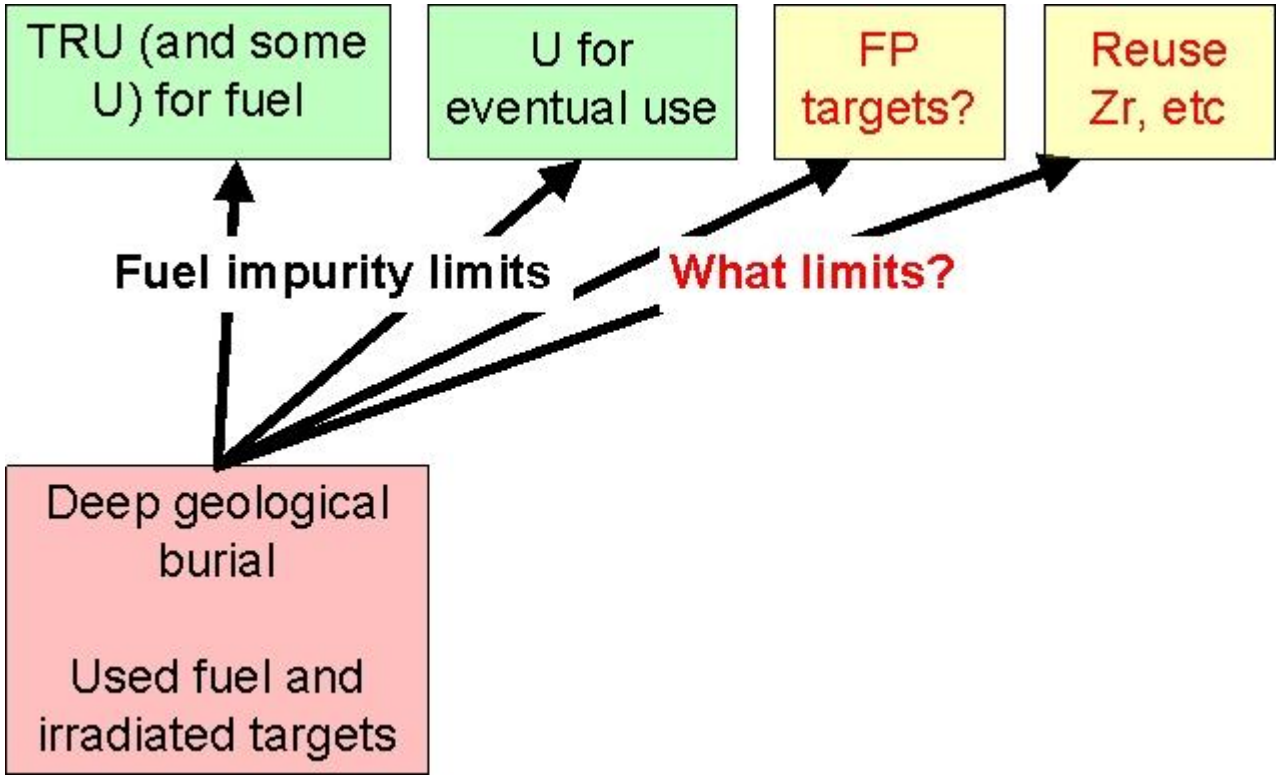
If we want to move stuff out of "used fuel", where might it go?

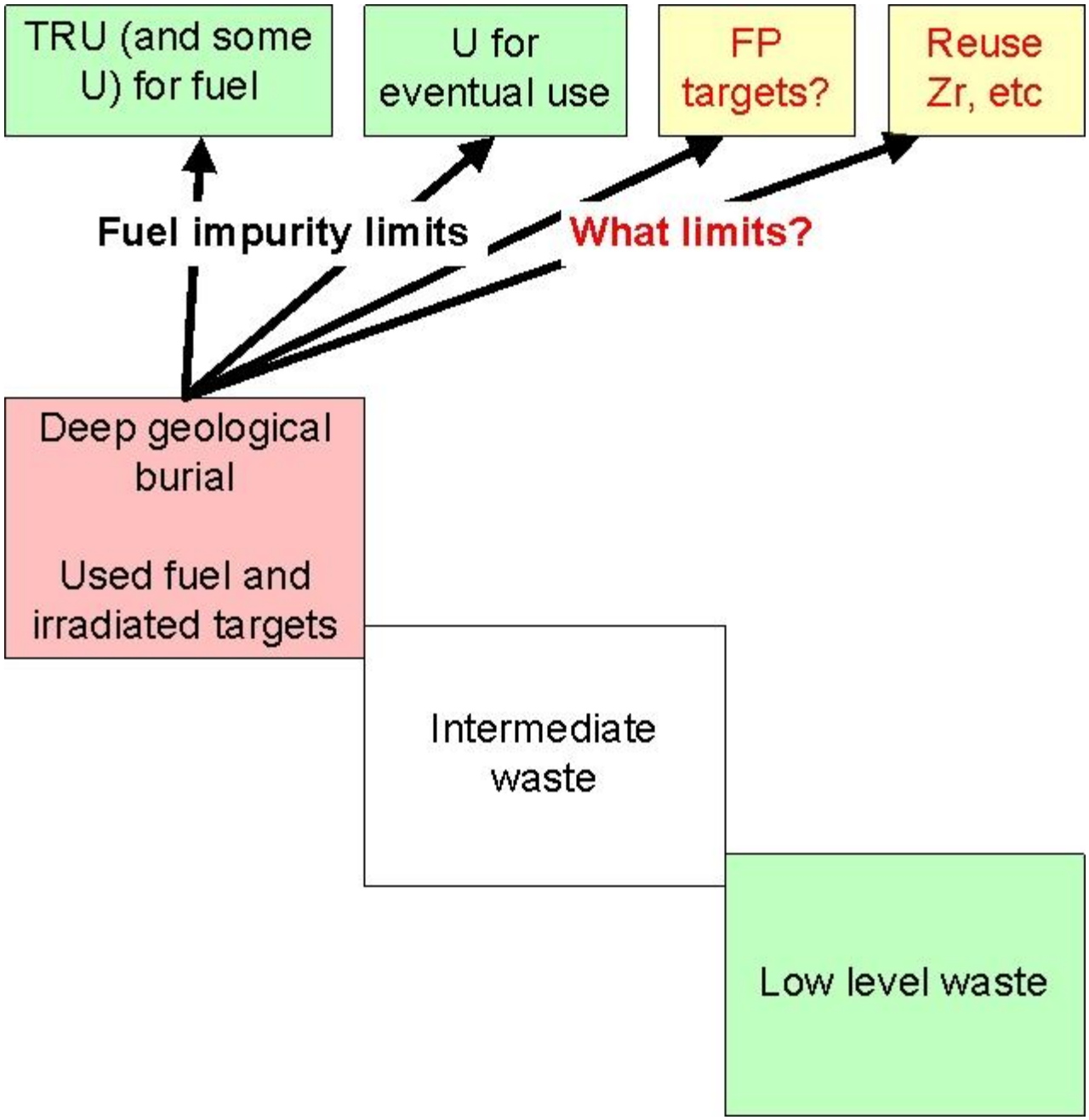




Must have a place to take it

And rules for determining when you can move it


TRU (and some U) for fuel
U for eventual use
FP targets?
Reuse Zr, etc
Fuel impurity limits
What limits?
Deep geological burial
Used fuel and irradiated targets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Deep geological burial
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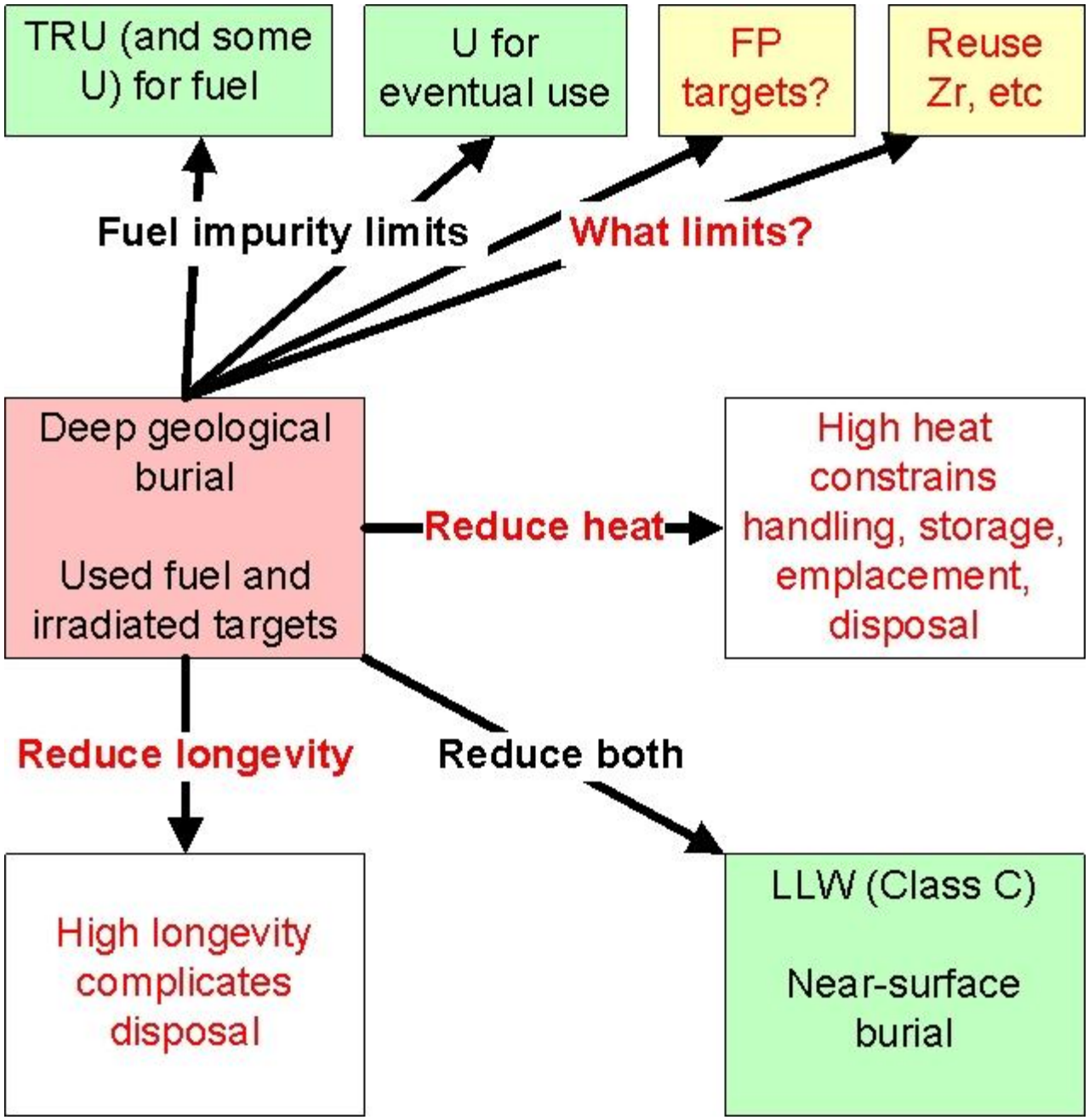
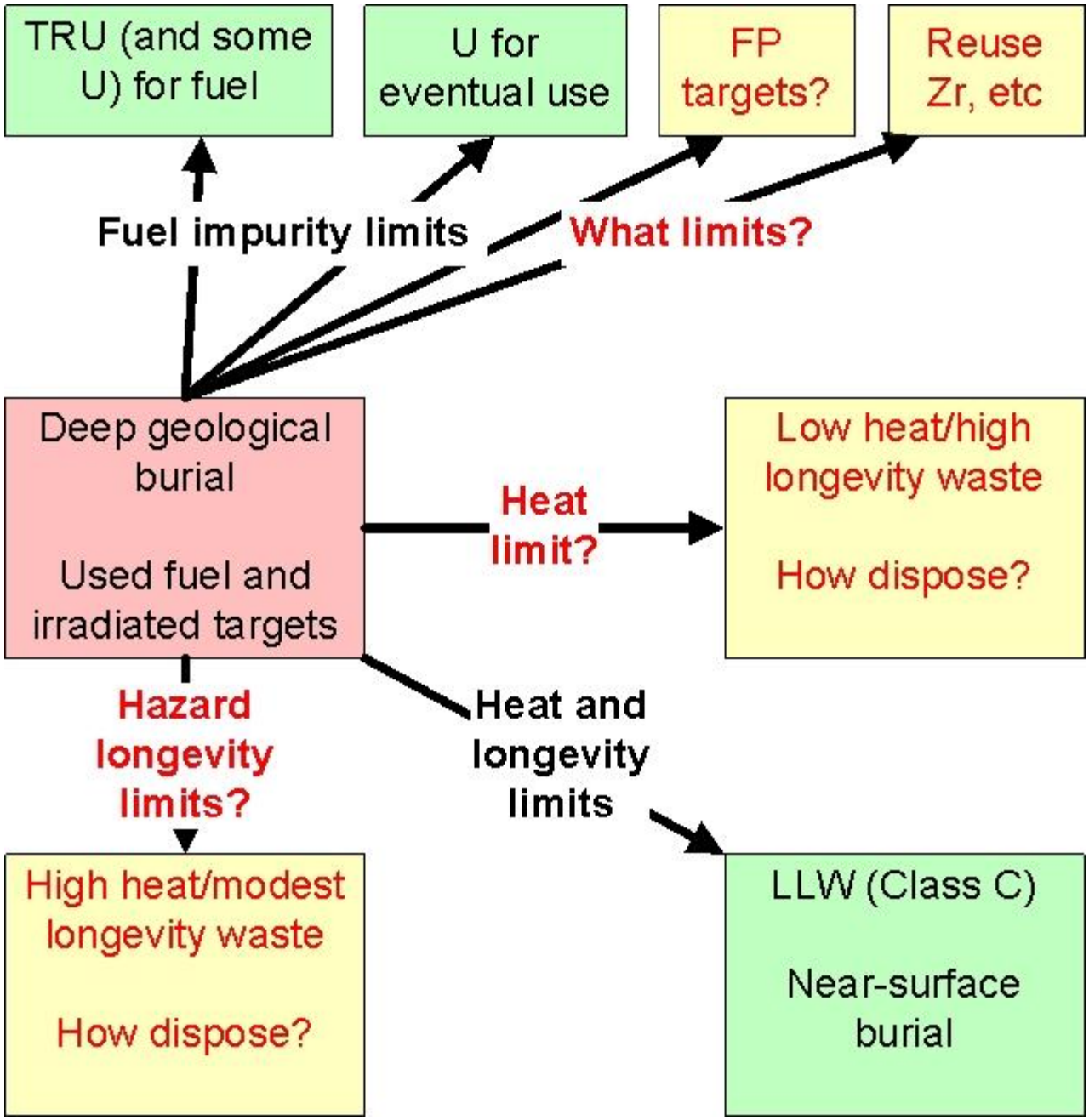
Intermediate waste
Low level waste


TRU (and some U) for fuel
U for eventual use
FP targets?
Reuse Zr, etc
Fuel impurity limits
What limits?
Deep geological burial
Used fuel and irradiated targets
Reduce heat
High heat constrains handling, storage, emplacement, disposal
Reduce longevity
Reduce both
High longevity complicates disposal
LLW (Class C)
Near-surface burial


TRU (and some U) for fuel
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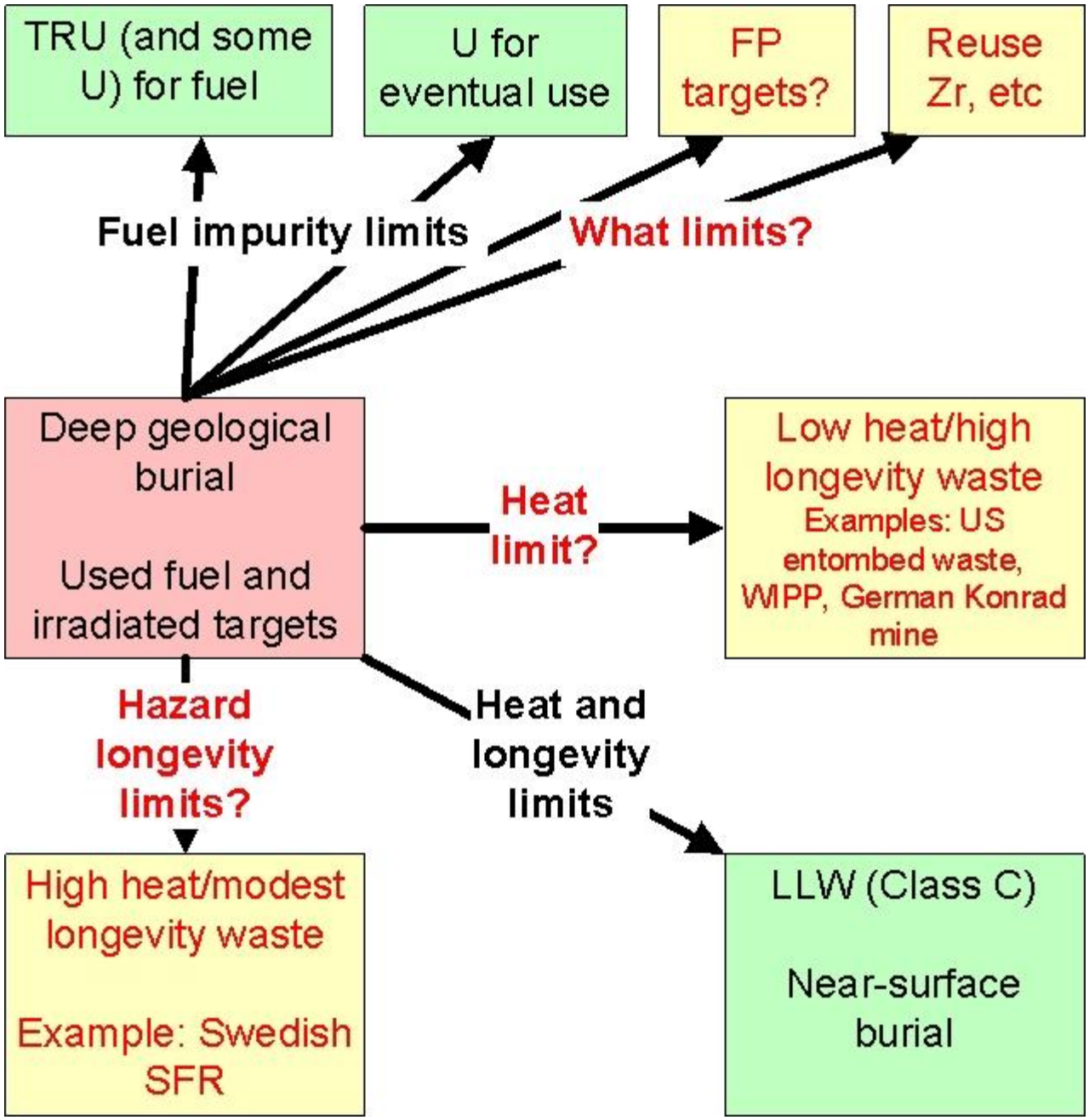
FP targets?
Reuse Zr, etc
Fuel impurity limits
What limits?
Deep geological burial
Used fuel and irradiated targets
Heat limit?
Low heat/high longevity waste
How dispose?
Hazard longevity limits?
Heat and longevity limits
High heat/modest longevity waste
How dispose?
LLW (Class C)
Near-surface burial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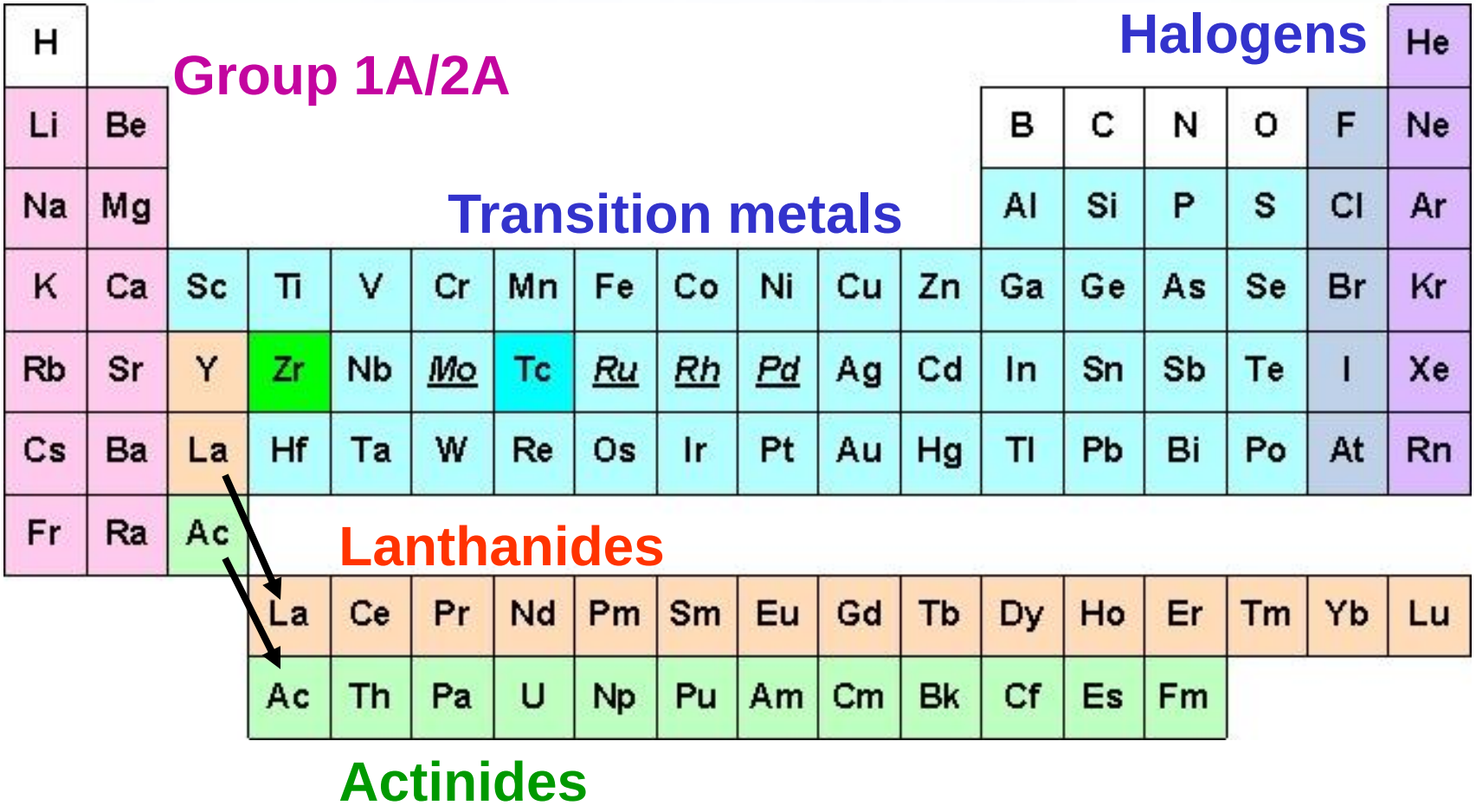
Fuel impurity limits
What limits?
Deep geological burial
Used fuel and irradiated targets
Heat limit?
Low heat/high longevity waste
Examples: US entombed waste, WIPP, German Konrad mine
Hazard longevity limits?
Heat and longevity limits
High heat/modest longevity waste
Example: Swedish SFR
LLW (Class C)
Near-surface burial

What do we have to contend with?



Re-use/recycle possibilities

- Single recycle doesn't solve the problem.
- **Multi-recycle with all transuranics and a few percent of the U**
  - LWR with MOX
  - LWR with heterogeneous assemblies of IMF/UOX pins
  - Analogous options with HTGR**?**
  - Fast reactors with TRU conversion ratio < 1
- **Multi-recycle with all transuranics with all the U**
  - Fast reactors with TRU conversion ratio > 1
- Bonus – non-fuel materials
  - LWR Zr cladding
  - FR Zr-alloy fuel
  - Graphite in HTGR

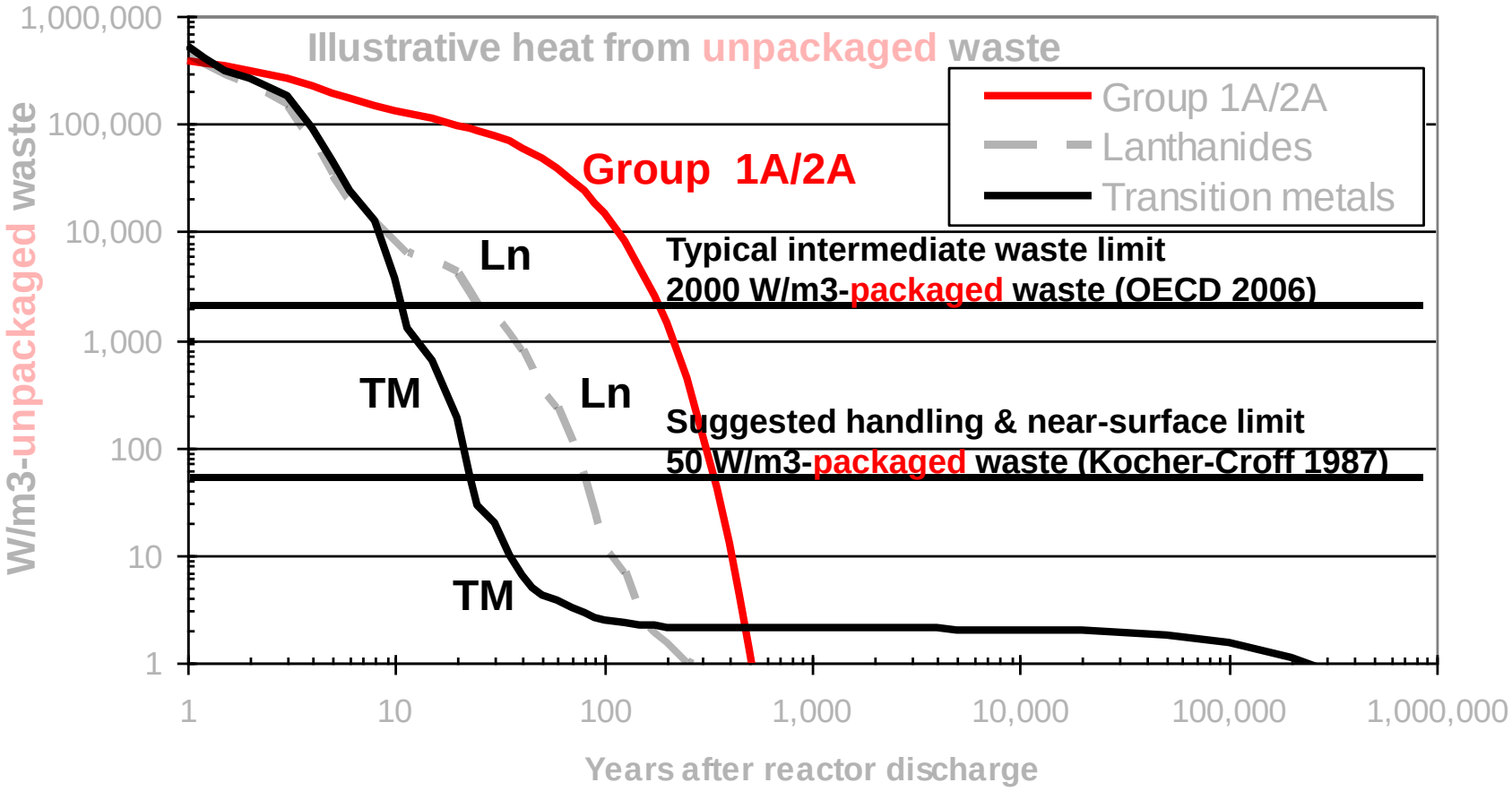
Score card: what is theoretically possible?

	Recycle?			
TRU	Yes			
Uranium	Partial unless breeder			
Zirconium	Maybe			
Lanthanides	No			
Transition metals	No			
Group 1A/2A	No			
Halogens	No			
Inert gases	No			
H-3	No			
C-14	If graphite			
Tc-99	No			

Score card: what is theoretically possible?

	Recycle?	Transmute residual stuff?		
TRU	Yes	N/A		
Uranium	Partial unless breeder	N/A		
Zirconium	Maybe	No		
Lanthanides	No	No		
Transition metals	No	No		
Group 1A/2A	No	Unlikely		
Halogens	No	Maybe		
Inert gases	No	No		
H-3	No	No		
C-14	If graphite	No		
Tc-99	No	Maybe		

Depending on waste density, packaging, criteria, and purity, disposal of lanthanides & transition metals may not be heat-limited



Score card: what is theoretically possible?

	Recycle?	Transmute residual stuff?	Pass heat criteria?	
TRU	Yes	N/A	No	
Uranium	Partial unless breeder	N/A	Yes	
Zirconium	Maybe	Unlikely	Maybe	
Lanthanides	No	No	Maybe	
Transition metals	No	No	Maybe	
Group 1A/2A	No	Unlikely	No	
Halogens	No	Maybe	Yes	
Inert gases	No	No	Yes	
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Potential radiotoxicity longevity criteria

- 100 nCi-TRU/g-packaged-waste (alpha-emitters, halflife >20 yr)
  - *40CFR191*
- 100 nCi-TRU/g-packaged-waste (alpha-emitters, halflife >5 yr)
  - *10CFR61*
- Limits for specific isotopes
  - Many potentially relevant isotopes are not in 10CFR61
  - When take the 10x metal waste form credit?
  - Fetter extended 10CFR61 analysis to all isotopes, halflife >5 yr.
    - *S. Fetter, E. T. Cheng, and F. M. Mann, "Long-Term Radioactivity in Fusion Reactors," Fusion Engineering and Design, 1988.*
    - *S. Fetter, E. T. Cheng, and F. M. Mann, "Long-Term Radioactive Waste from Fusion Reactors: Part II," Fusion Engineering and Design, 1990.*

Preliminary screening: isotope limits

- 100 nCi-TRU/g-packaged-waste (>5 yr) & limits for Pu241, Cm242 limits
  - ➔Pu and Am constrains lanthanides and Group 1A/2A – preliminary estimate is a limit of ~0.1% Pu or Am getting into waste
  - ➔Letting Pu241 decay into Am241 toughens constraint
- Expanded 10CFR61 isotope concentration limits
  - Constrains: U+TRU, halogens (I129), Tc99, transition metals (Sn126)
  - Maybe ok: Lanthanides (Ho166m), Group 1A/2A (what Cs135 limit?)
  - Not constrained: Inert gases, H3
- Others?

Score card: what is theoretically possible?

	Recycle?	Transmute residual stuff?	Pass heat criteria?	Pass radiotoxicity criteria?
TRU	Yes	N/A	No	No
Uranium	Partial unless breeder	N/A	Yes	Yes if clean
Zirconium	Maybe	Unlikely	Maybe	Maybe
Lanthanides	No	No	Maybe	Likely if clean
Transition metals	No	No	Maybe	No
Group 1A/2A	No	Unlikely	No	Maybe
Halogens	No	Maybe	Yes	No
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Halogens		Maybe	Yes	
Inert gases			Yes	Yes
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Tc-99		Maybe	Yes	

To avoid making HLW need at least one yes in each row

	Recycle?	Transmute residual stuff?	Pass heat criteria?	Pass radiotoxicity criteria?
Which strategies needed?	**YES**	**Helpful but not required**	**YES**	**YES**
TRU	**Only choice**			
Uranium	Partial unless breeder		Yes	Yes if clean
Zirconium	Maybe		Maybe	Maybe
Lanthanides			Maybe	Likely if clean
Transition metals			Maybe	
Group 1A/2A				Maybe
Halogens, Tc-99		Maybe	Yes	
Inert gases, H-3			Yes	Yes if clean
C-14	If graphite		Yes	Maybe

To avoid making HLW need at least one yes in each row

Heat mgt

TRU content

	Recycle?	Transmute residual stuff?	Pass heat criteria?	Pass radiotoxicity criteria?
Which strategies needed?	**YES**	**Helpful but not required**	**YES**	**YES**
TRU	**Only choice**			
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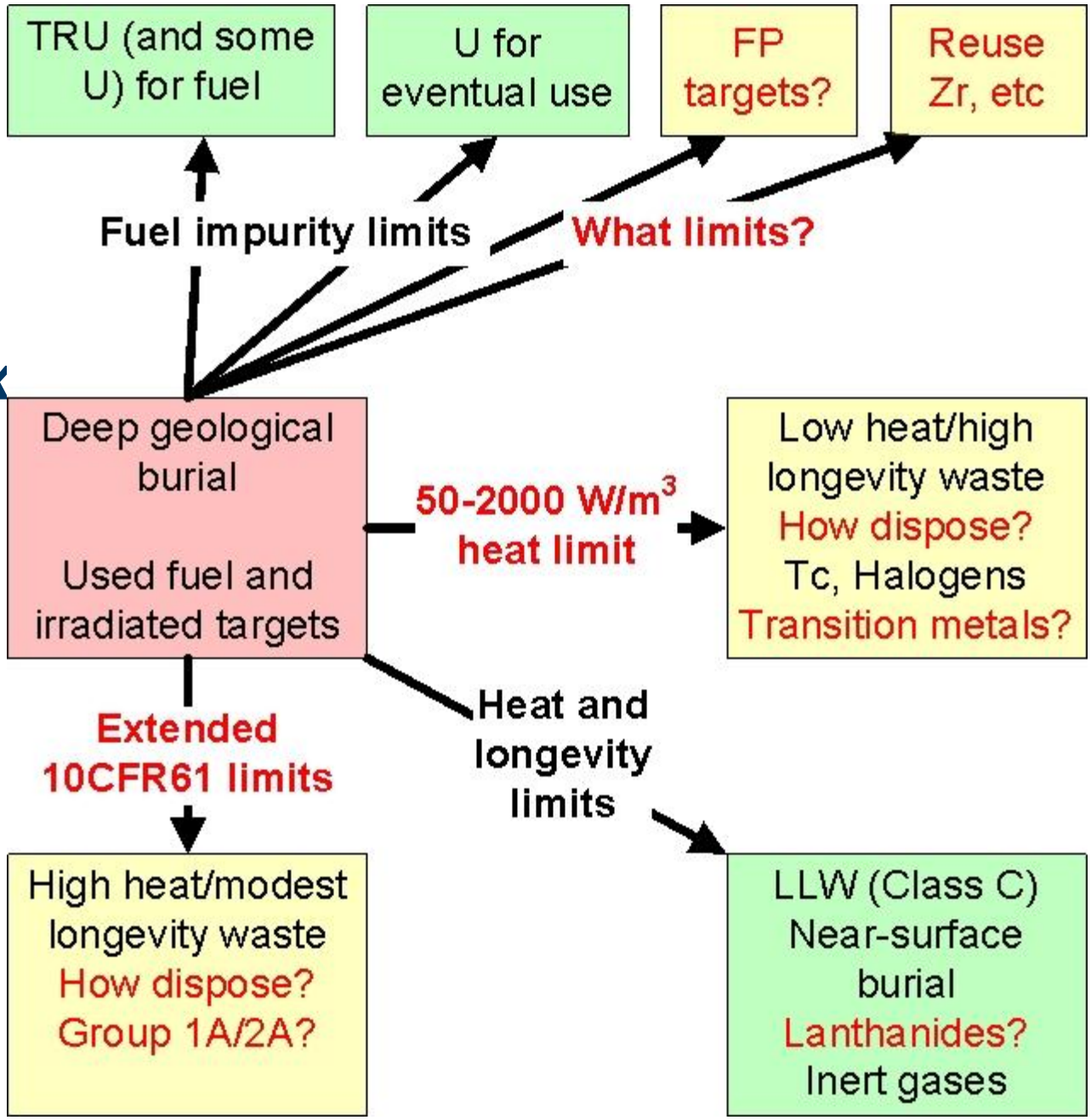
Group 1A/2A				Maybe
Halogens, Tc-99		Maybe	Yes	
Inert gases, H-3			Yes	Yes if clean
C-14	If graphite		Yes	Maybe

A recycle scenario has to specify what goes into what box

- One can view each set of criteria and yes/no decision piece-meal or consider the entire system
- Example: if allow more lanthanides into fuel; both echem and aqueous experts say less TRU into lanthanide-rich waste.



Must Advanced Fuel Cycles Produce High-Level Waste? Not necessarily

- Hypothetical avoidance of HLW does not necessarily mean no “geologic repository” but it would reduce uncertainties associated with combining high-heat/high-longevity in the same waste and allow us to say disposal precedents exist for all waste we’d produce.
  - Disposal precedents exist for high-heat/low longevity, low-heat/high longevity, and low-heat/low longevity.
  - No precedents exist for high-heat/high longevity, i.e. HLW.
- **Regulatory** and **disposal** pathways for high-heat/low-longevity and low-heat/high-longevity waste streams?
- Affordable **separations**?
  - Must keep TRU out of waste.
  - Can **fuels** tolerate relatively high impurities, esp. lanthanides
  - Zr, steel sufficiently clean for re-use?
- Clever heat management?
- Appropriate **waste** forms?
  - Reduce chemical perturbation (and associated uncertainties) of disposal sites?
- Can the pieces fit together?